

094549.08310  
T07E80.26454660

CLOSED-LOOP COLOR CORRECTION USING FACTORY-MEASURED  
COLOR CUTOFFS ANCHORED TO FIELD-MEASURED WHITE POINT

RELATED PATENT DOCUMENTS

Closely related documents are other, coowned U. S. utility-patent documents — hereby wholly incorporated by reference into this document. One such document is in the names of Francesc Subirada et al., application serial 09/919,207 entitled "LINEARIZATION OF AN INCREMENTAL PRINTER BY MEASUREMENTS REFERRED TO A MEDIA-INDEPENDENT SENSOR CALIBRATION" — later issued as U. S. Patent 6,\_\_\_\_,\_\_\_\_. Another such document is also of Subirada et al., U. S. application serial 09/034,722, "SCANNING AN INKJET TEST PATTERN FOR DIFFERENT CALIBRATION ADJUSTMENTS", issued as U. S. 6,\_\_\_\_,\_\_\_\_; another of Thomas H. Baker et al., serial 09/183,819 entitled "COLOR-CALIBRATION SENSOR SYSTEM FOR INCREMENTAL PRINTING" issued as U. S. 6,\_\_\_\_,\_\_\_\_; yet another of Ramón Borrell, serial 09/252,163 entitled "PIXEL-DENSITY AUGMENTATION AND ADJUSTMENT WITH MINIMUM DATA, IN AN INCREMENTAL PRINTER" issued as U. S. 6,\_\_\_\_,\_\_\_\_; still another of Soler et al., serial 09/919,260 entitled "COMPENSATING FOR DRIFT AND SENSOR PROXIMITY IN A SCANNING SENSOR, IN COLOR CALIBRATING INCREMENTAL PRINTERS", later issued as U. S. 6,\_\_\_\_,\_\_\_\_; and another of Francis Bockman and Guo Li, entitled "CONSTRUCTING DEVICE-STATE TABLES FOR INKJET PRINTING", U. S. application serial 08/960,766, issued as U. S. 6,\_\_\_\_,\_\_\_\_.

1     FIELD OF THE INVENTION

2  
3             This invention relates generally to machines and pro-  
4     cedures for incremental printing of text or graphics on  
5     printing media such as paper, transparency stock, or other  
6     glossy media; and more particularly for such methods and  
7     apparatus that construct text or images from individual  
8     ink spots created on a printing medium, in a pixel array.  
9     Although for definiteness and simplicity much of this doc-  
10    ument is couched in terms of a scanning thermal-inkjet ma-  
11    chine and method, the invention is equally applicable to  
12    the several other forms of incremental printing that are  
13    subject to variation of marking density as among print-  
14    heads. The invention uses lab-collected high-tonal-densi-  
15    ty data as a standard to avoid uncontrolled color varia-  
16    tions among printers within a product line.

17  
18  
19  
20    BACKGROUND OF THE INVENTION

21  
22             Some amount of color variation is inherent in all  
23    printing processes. Inkjet printing is no exception.

24             Many sources of color variation have been character-  
25    ized. The two most important of these appear to be dot-  
26    size variations and hue variations.

27             The first of these, variation in dot size, is largely  
28    due to drop-weight variation or dot-gain variation. The  
29    second, hue variation, is sometimes due in turn to dot-  
30    size variation — but perhaps more sensitively to environ-  
31    mental ink-to-media interactions.

32  
33             (a) Graphic-arts requirements — Consistency of  
34    color reproduction is important in all printing processes,

1 but particularly so in production or commercial work.  
2 Accordingly for incremental printers that are designed  
3 especially for commercial use, it is especially important  
4 to control reproduction of color via closed-loop measure-  
5 ment and correction.

6 Color consistency or reproducibility, i. e. preci-  
7 sion, is a different matter from color accuracy — al-  
8 though as usual accuracy is in principle attainable only  
9 to the extent that there is precision. Accuracy is rela-  
10 ted to precision as a mean value or time average 11 (Fig.  
11 1) of a varying parameter 12 is related to the extent 13  
12 of variation.

13 For a modern-day printing product, particularly in  
14 the multitasking environment, color performance immediate-  
15 ly after calibration is limited by the I. C. C. profile  
16 capability. (The initials "I. C. C." stand for the "In-  
17 terColor Consortium", which has developed the industry-  
18 standard "profile" or color-mapping protocol for convert-  
19 ing input image file data, e. g. a TIFF file, into device  
20 CMYK values, with correction for color differences.)

21 For the statistical 95% confidence level throughout  
22 the printer gamut and product line, a mean-accuracy goal  
23 (Fig. 2) is  $dE = 4$ . (The notation " $dE$ " is a shorthand for  
24  $dE^*_{ab}$ , which is the root-mean-square Euclidean distance  
25 between two colors in the  $L^*a^*b^*$  color space.) Corre-  
26 spondingly a total color error (" $TCE$ ") goal is  $dE = 9$ .

27 Such performance requires that the degree of consis-  
28 tency in color accuracy possess a robustness to all the  
29 possible sources of color variation from the nominal.  
30 This includes changes in environment, printheads, media  
31 lots and so forth. Some of these changes typically intro-  
32 duce color variations so large as to swamp out all cali-  
33 bration efforts, and therefore simply constitute a re-  
34 quirement for recalibration.

Furthermore, once again, such achievement is assumed to be available only within a limited time after calibration. Hence a user who relies upon a printer for a livelihood — e. g. a graphic-arts professional — should be warned to perform the calibration on a regular basis, to keep the machine within the goals indicated. In view of these considerations, assuming full-time use, color calibrations are required weekly and also at each change of printhead or media.

(b) Related work in the art — Recent efforts by others have attacked problems of reliable field linearization in an incremental printer using a so-called "line sensor" — already present in the printer for use in interhead alignment and the like — in color-tone pseudodensitometry. Though the linearization is a field operation, a groundwork for these procedures begins with calibration of the sensor itself, preferably treated as media-independent calibration and performed at the factory.

(In some variants, a sensor calibration can be obtained with no field measurements at all — and therefore can be performed in the field, using tabulations of those colorant properties, or can simply be loaded into the printer as a complete calibration data set. Such calibration is based upon known spectral properties of the colorants that are loaded into the printer. Either the colorant properties or the calibration data as such can be, for instance, downloaded from the printer manufacturer via the WorldWide Web.)

Thereafter, with a line sensor precalibrated, linearization proceeds in the field by automatic printing of a tonal ramp, and using that sensor to measure the printed ramp. The linearization also includes — first for black-and-white colorant measurements — normalizing the sensor

readings with respect to the tonal range between reflection from unprinted printing medium and the nominal maximum black tone.

Measurements of reflection from the unprinted medium are adequately precise and accurate, particularly in view of the advantageously high light level and therefore good signal-to-noise ratio for such measurements. Somewhat the contrary is the case of determinations at the other end of the printer dynamic range, where the light level in a black tone is by definition extremely low.

As a practical matter, fortunately, this black tone may in fact be treated as zero signal in the sensor. Alternative assumptions about its level may be made instead, to cope with the very great difficulty of accurately measuring, with pseudodensitometric equipment, the very low light levels involved. (For example the system may sense a dark region provided in the printer for the purpose.) In any event the normalized sensor gray-scale pseudodensitometric readings are called "absolute contrast ratios", abbreviated "ACR".

As to chromatic-colorant measurements, however, maximum-saturated chromatic tones cannot be considered equal to zero in light level and cannot otherwise readily be fixed to any alternative true standard. Therefore the conventional field linearization has simply proceeded on the assumption that those maximum chromatic-colorant tones are correct — and accordingly that each such tone should and must merely be accepted, as-is, to form one established endpoint of the tonal range to be linearized.

In effect the operation of each printhead was itself accepted as defining a color standard. Unfortunately, in the incremental-printing field printheads and inks are subject to significant tolerances in several parameters, leading to corresponding variations in inking density as

among inks, printheads and therefore printers in a product line.

Nevertheless conventionally these chromatic-colorant measurements are followed by normalization with respect to the tonal range between reflection from unprinted print medium and the actually measured nominal maximum chromatic-colorant tone. These normalized values are called "local contrast ratios", abbreviated "LCR".

In some such linearization procedures, the normalized chromatic tones (which as noted above are inaccurate due to product tolerances and absence of a pertinent color standard) may further be referred to the black-and-white normalized values, which in turn are somewhat unreliable because of the above-mentioned assumptions in dealing with the black level.

Based upon nonlinearity in the normalized, adjusted and referred readings, these earlier procedures continue with determination of a correction function needed to establish linearity in the readings. They then store the correction function for use as a calibration of the printer in subsequent printing.

Such methods are adequate to correct for life effects and other variabilities that may occur among different sensors, in the absence of an on-line characterization for each individual sensor. For linearization purposes alone, they are sufficient.

Due to the limitations noted above, although the pseudodensitometric sensor systems can respond to relative tonal differences they are not capable of reliable absolute tonal readings. Accordingly these earlier systems yield reasonably well linearized hardcopy printouts but not absolute consistency — particularly not reliable consistency as among different printers, different printheads or different ink sets.

1           Methods described in the foregoing discussion have  
2       been introduced for printers in certain specialized mar-  
3       kets. These include, in particular, machines for printing  
4       high-quality images of photograph-like subject matter.

5           Such devices are generally outfitted with correspond-  
6       ingly specialized printheads — e. g., in some cases,  
7       heads selected for extremely high uniformity of inkdrop  
8       weight. In some cases the printheads may be in matched  
9       sets of different colorants to be used together.

10          Those specialized printers are used only for art-  
11       quality reproductions, fine posters and the like. There-  
12       fore the additional cost of selected and even matched  
13       heads is readily justifiable.

14          Another approach that may be justified for specia-  
15       lized, high-end machines is provision of a fully qualified  
16       onboard colorimeter — as suggested, for example, by the  
17       previously mentioned patent document of Baker. It will be  
18       understood, however, that neither the expense of matched  
19       heads nor that of built-in colorimetry is normally accep-  
20       table in machines for regular commercial work.

21          Still another design philosophy is that taught by  
22       Bockman and Li in their patent document mentioned earlier.  
23       That philosophy calls for memorization of a large number  
24       of device color states distributed substantially through-  
25       out the color-solid gamut of the apparatus.

26          This philosophy too clearly is suited only for a rel-  
27       atively specialized and relatively high-end system. Even  
28       so, retention of that rather monumental amount of data  
29       does not alone necessarily ensure absolute uniformity of  
30       the rendered colors as among different unit printers of  
31       the product line.

32  
33          (c) A more-demanding context — In another printing  
34       environment, particularly for use in multitasking machines

such as designed for very-short-run commercial printshops, the normalization and linearization procedures outlined above would result in a greater error, which would be unacceptable for routine commercial work. One major reason for this is that in the highly competitive multitask market inkjet dropweights are substantially more variable.

In particular whereas nominal dropweight in such a machine may be 3.25 ng, economic considerations dictate that production tolerances in nozzle, heater, firing chamber and ink characteristics permit high-weight values as great as 4.5 ng. Such dropweights produce correspondingly elevated dot sizes and accordingly — when such dots merge on the printing medium — maximum tones that are subject to a magnified luminosity error 15 (Fig. 3).

For the dropweight variation just specified, this error is roughly 5 dL\* units. The tone density is higher than nominal, and luminosity accordingly 5 units lower. This is an example of system performance if doing only primary linearization.

In the graph, the curved lines 16, 17 exhibit the raw LCR data for the nominal-dropweight and high-dropweight printheads respectively. In other words, these curved lines 16, 17 represent the intrinsic or natural responses of the apparatus, and most particularly of area-filling geometries for different ratios of inkdrop diameters to the spacing-apart of inkdrop centers. These area-filling geometries are further perturbed and greatly complicated by divergent coalescence behavior of different-size inkdrops, and of inkdrops on different printing media, and of inkdrops under various operating conditions.

The distance between inkdrop centers is defined by pixel dimensions. These pixel definitions in turn are set by two sets of machine operating parameters:



- 1 (1) the firing frequencies along each row — thus es-
- 2 tablishing pixel-column spacings — and
- 3
- 4 (2) printing-element spacing along the print-element
- 5 arrays, and print-medium advance distance — which
- 6 establish pixel-row spacings.

7

8 Unfortunately the geometrical relationships between ink-

9 drop areas and spacings cause printed tonal ramps to be

10 nonlinear in tonal steps, even when the nominal inking

11 density — as defined in terms of fractions of pixels

12 inked — is increased in linear steps with a single drop

13 diameter.

14 Not only are the relationships between pixel-fraction

15 inking and actual area coverages nonlinear, due to these

16 geometrical factors, but in addition the specific nonlin-

17 ear behavior itself varies with inkdrop diameter. This is

18 the reason for the difference in endpoints 62, 64 of the

19 natural response curves 16, 17 obtained for data from two

20 printheads with different dropweights.

21 The luminosity discrepancy 15 appears at the low-lu-

22 minosity end 62, 64 of the printer dynamic range — i. e.

23 the high-density operating cutoff points. This is so even

24 though at the high-luminosity end 69 the same curves 16,

25 17 are aligned.

26 The dashed straight lines 18, 19 exhibit the results

27 of linearizing those two data sets with the nominal- and

28 high-dropweight printheads respectively. Earlier artisans

29 in this field — particularly in the related work dis-

30 cussed in subsection (b) above — have substituted these

31 rectilinear responses 18, 19 are substituted for the

32 intrinsic or natural curvilinear responses 16, 17 of the

33 apparatus, by preadjusting the image data (before print-

34 masking).

Those substitutions were definitely beneficial. They are a fundamental first step toward systematic control of colorimetric linearity in primary colors — and thereby toward orderly combinations and relationships among the secondary and other constructed colors that result from grouping primary-ink dots together. The color-combining properties articulated by Grassman's laws, and assumed in maneuvering within color space, rely upon such linearity.

Such preadjustments can be first grasped at a conceptual, graphic level as application of a conversion function 61, 63 (Figs. 4 and 5) that is simply complementary to the intrinsic or natural transfer function 16 or 17, respectively of the apparatus. This conceptual representation resides in the generally symmetrical shape of the conversion functions 61, 63 relative to the natural response functions 16, 17 respectively — particularly when viewed as referred to the desired ideal straight-line responses 18, 19 respectively. Curves for the conversions 61, 63 are upward-concave; for the natural responses 16, 17, -convex.

To promote this conceptual understanding, in Figs. 4 and 5 the correction functions 61, 63 are positioned in alignment with the original, natural responses 16, 17. In particular, in the nominal-dropweight case both the original response 16 and the corresponding correction function 61 diverge from a first common, high-luminosity point 69.

They reconverge at the low-luminosity ends in a second common point, the high-density cutoff 62. Analogously in the high-dropweight case both the original response 17 and corresponding correction function 63 diverge from a first common, high-luminosity point 69 and reconverge in a common low-luminosity cutoff point 64.

1           There is, however, no crosstalk, or causality as be-  
2           tween the two cases. That is to say, nothing in either  
3           Fig. 4 or Fig. 5 has any influence on phenomena graphed in  
4           the other of these two illustrations.

5           In these conceptual illustrations (which are not to  
6           scale) the magnitudes of the corrections actually are rep-  
7           resented by the differences between the correction func-  
8           tions 61, 63 and the ideal, rectilinear functions 18, 19.  
9           (This is roughly only half the difference between the il-  
10          lustrated correction functions 61, 63 and the natural re-  
11          sponses 16, 17.)

12  
13          A somewhat more quantitative grasp (though still not  
14          to scale) of the correction functions 61, 63 may be ob-  
15          tained by considering the same two functions shown alter-  
16          natively as additive signal corrections  $\Delta S$  and multipliers  
17          M (Fig. 6). As a practical matter, these corrections can  
18          in fact be readily derived and then applied either as ad-  
19          ditive functions  $\Delta S$ , 61, 63 or as multiplicative functions  
20          M, 61, 63.

21          Thus the additive adjustments  $\Delta S$  are pictured here as  
22          referred to a zero (0.0) baseline, whereas the multipliers  
23          M are shown referred to a unity (1.0) baseline. In each  
24          of these two cases, the right-hand (high nominal density)  
25          end of the correction curve 61 or 63 ends at the same lev-  
26          el (0.0 or 1.0 respectively) as the left-hand (low nominal  
27          density) end.

28          In either event the correction terms  $\Delta S$  or correction  
29          factors M do not represent mere observed errors or desired  
30          compensations. Rather these quantities are physically ap-  
31          plied to modify input image data before halftoning — to  
32          effectuate an actual and precise linearization within the  
33          operations of a given single printer.

1 No such linearization, however, can cure the problem  
2 of the endpoint or cutoff-point divergence 15 (Fig. 3).  
3 This degree of divergence is readily noticeable even in a  
4 single-primary-colorant region of an image.

5 If such a single primary colorant is combined with  
6 another primary, this divergence goes far beyond being  
7 readily noticeable, and can be extremely conspicuous in  
8 terms of hue distortions. It is particularly conspicuous  
9 if the dropweight of that other colorant is nominal or  
10 relatively low.

11 Another factor that greatly exaggerates tonal error  
12 due to dropweight variation is use of so-called "light"  
13 inks: for example, light magenta or light cyan. For such  
14 colorants a curve of luminosity vs. colorant pixel density  
15 ends at various points, without at all approaching a satu-  
16 ration point for the full-strength colorant — i. e. any  
17 tone corresponding to an almost-constant  $L^*$  value.

18 Using such inks, no approximation or simplification  
19 is available to circumvent the tonal and hue errors that  
20 can survive these earlier linearization systems. The dis-  
21 tribution of errors considered statistically — in partic-  
22 ular the 95% error, would also be roughly 5  $dL^*$ .

23  
24 (d) Conclusion — Thus color inconsistencies among  
25 different printers within a single product line have con-  
26 tinued to impede achievement of uniformly excellent inkjet  
27 printing — at high throughput — on all industrially im-  
28 portant printing media, but still at minimal cost such as  
29 associated with a low-end multitasking printer. Thus im-  
30 portant aspects of the technology used in the field of the  
31 invention remain amenable to useful refinement.

32  
33  
34

SUMMARY OF THE DISCLOSURE

The present invention introduces such refinement. In its preferred embodiments, the present invention has several aspects or facets that can be used independently, although they are preferably employed together to optimize their benefits.

In preferred embodiments of a first of its facets or aspects, the invention is a method of color-calibrating an incremental printer. The method includes the step of, for each of plural colorants respectively, defining at least one standard maximum tone.

It also includes the step of establishing an absolute perceptual parameter of the at least one defined maximum tone. The method further includes the step of — in substantially each printer or printer driver of a product line — storing a numerical representation of the established absolute parameter for later use in color-correction calculations for the printer.

The term "plural colorants" used above does not necessarily mean all the colorants that are in use in the printer. The invention yields its greatest benefits when applied with respect to colorants that are hardest to roughly standardize by other methods — as, for instance light colorants (e. g. light magenta, light cyan).

The invention has perhaps least impact when applied with colorants that are easiest to roughly standardize by other techniques — particularly black. As a matter of preferences, the "plural colorants" mentioned above include at least all the chromatic colorants in use.

The phrase "at least one standard maximum tone" is intended to encompass three variants:

- 1       ▪ preferably at least one such tone as printed using
- 2       each combination of printmode and printing medium for
- 3       which the printer is intended; and
- 4
- 5       ▪ possible updated tones or established perceptual val-
- 6       ues that may be made available (e. g. via the Inter-
- 7       net or other network, or on a floppy disc) for use in
- 8       the printer after sale.
- 9

10      Other variations, however, are within the scope of this

11      language.

12

13           The foregoing may represent a description or defini-

14      tion of the first aspect or facet of the invention in its

15      broadest or most general form. Even as couched in these

16      broad terms, however, it can be seen that this facet of

17      the invention importantly advances the art.

18           In particular, this aspect of the invention recogni-

19      zes that the inability of earlier procedures to provide a

20      standardized color performance throughout a population of

21      color printing machines is a problem that flows first from

22      an absence of any standard — and then furthermore from an

23      absence of characterizing information about such standard.

24      The first aspect of the present invention accordingly both

25      defines a standard and establishes a quantification of it.

26           Because the second step is not in absolute, not rela-

27      tive terms it is portable — i. e., susceptible to being

28      stored in one place and environment, for recall later in a

29      different environment and place to guide a control para-

30      digm that in fact produces standardized color. The inven-

31      tion does not, however, specify memorization of an entire

32      three-dimensional color calibration — but rather resolves

33      the problem in an elegant fashion that invokes only a very

34      minimum of data-storage and computational resources.



1 measuring the absolute perceptual parameter for each  
2 of representative printers in the product line, and  
3 selecting from among the measurements; or measuring  
4 the absolute perceptual parameter for each of repre-  
5 sentative printers in the product line, and combining  
6 the measurements;

7  
8 ■ the defining, establishing and storing steps operate  
9 with respect to substantially exclusively a single  
10 tone for each colorant, as distinguished from record-  
11 ing an entire colorimetric calibration throughout a  
12 tonal range — so that the invention does not under-  
13 take to memorize device states or the like within an  
14 entire color-calibration solid as generally taught by  
15 the patent document of Bockman and Li; and

16  
17 ■ the method further include the step, performed in an  
18 end-user facility, of automatically applying the  
19 stored numerical representation in calculations for  
20 color correction in the printer.

21  
22 If this last-mentioned basic preference is in effect,  
23 then it is further preferred that, for each chromatic col-  
24 orant respectively, the applying step include contracting  
25 or expanding the printer dynamic range to force a maximum  
26 tone printed by the printer to match the defined standard  
27 tone. This subpreference as to dilation of dynamic range,  
28 in turn, is subject to several subsidiary preferences.

29 One of these is that the defining and establishing  
30 steps include determining the absolute perceptual parame-  
31 ter for printers that represent extremes of performance of  
32 the product line. In this case the defining and estab-  
33 lishing steps go on to selecting the numerical representa-  
34 tion — and selecting printer operating conditions — in





094549 0830 26454660

1 ing the correction upstream of printmasking. It is also  
2 very highly preferable that the method include, in the  
3 data-collection laboratory stage, determining the maximum  
4 tone printed under worst-case or extreme operating condi-  
5 tions — so that the standard tone or tones, and also many  
6 other operating parameters, can be selected in such a way  
7 as to be certain that every printer in the line will be  
8 able to reach the standard tone.

11 In preferred embodiments of its second major indepen-  
12 dent facet or aspect, the invention is a method of color-  
13 calibrating an incremental printer in an end-user facil-  
14 ity. The method includes the step of, for each of plural  
15 colorants in the printer retrieving from the printer or a  
16 printer driver a stored numerical representation of an ab-  
17 solute perceptual parameter for a standard maximum tone.

18 It also includes the step of applying the retrieved  
19 numerical representation in color-correction calculations  
20 for the printer. (The previous discussion of "plural col-  
21 orants" is applicable here as well; and, within the lit-  
22 eral meaning of the language here, in general the printer  
23 may retrieve one or more such stored numbers, for one or  
24 more such tones.)

26 The foregoing may represent a description or defini-  
27 tion of the second aspect or facet of the invention in its  
28 broadest or most general form. Even as couched in these  
29 broad terms, however, it can be seen that this facet of  
30 the invention importantly advances the art.

31 In particular, this second aspect of the invention is  
32 complementary to the first. It is this present facet that  
33 undertakes to make active use of available quantitative  
34 information in actually physically manipulating the opera-

tion of a printing machine to behave according to the established standard. The inventors believe that this has never been done before in an incremental color printer.

Although the second major aspect of the invention thus significantly advances the art, nevertheless to optimize enjoyment of its benefits preferably the invention is practiced in conjunction with certain additional features or characteristics. In particular, preferably for each chromatic colorant respectively the applying step includes contracting or expanding the printer dynamic range to force a maximum tone printed by the printer to match the defined standard tone.

In event this basic preference is observed, then preferably the method further includes the essence of the three-part preference described earlier — namely (1) inclusion of the step of, before the applying step, using the printer to print a specimen of the maximum tone, and measuring the absolute perceptual parameter for the specimen; (2) that the applying step further include employing the measured parameter for the specimen as an instance of the maximum tone printed in the absence of the contracting or expanding; and (3) that the contracting or expanding include forcing the measured absolute perceptual parameter for later-printed instances of the maximum tone to match the established absolute perceptual parameter for the defined standard tone.

Another subpreference is that the applying step further include linearizing later printing of the respective colorant, using the forced match as one endpoint of the linearizing. Yet another is that the contracting or expanding include cutting off maximum tonal density early for marking arrays that are marking too boldly, and ex-

094549"083101  
TOTEBO"26454660

1 tending maximum tonal density to cut off late for marking  
2 arrays that are marking too lightly.

3 Other preferences also mentioned earlier, in connec-  
4 tion with the first major aspect of the invention, are  
5 that the applying step include introducing the correction  
6 upstream of printmasking; and the method further includes  
7 the step of, before the retrieving step, downloading from  
8 a network an updated value of the numerical representa-  
9 tion. Another basic preference is that the applying step  
10 be performed in the printer by integrated circuits operat-  
11 ing programs.

12  
13 In this last-mentioned case it is also preferred that  
14 the applying step set the maximum tonal density that the  
15 printer can image, to match the stored numerical represen-  
16 tation. Another preference is that the method, still for  
17 each colorant, further include the step of printing a to-  
18 nal ramp. Here the measuring step includes using a cali-  
19 brated line sensor to measure the printed tonal ramp.

20 When the line sensor is thus used, preferably this  
21 using includes these substeps:

- 22
- 23 ■ assembling a set of sensor readings for each tone in  
24 the ramp;
  - 25
  - 26 ■ normalizing the readings with respect to the tonal  
27 range between reflection from unprinted printing me-  
28 dium and the maximum tone; and
  - 29
  - 30 ■ based upon nonlinearity in the normalized, adjusted  
31 and referred readings, determining a correction func-  
32 tion to establish linearity in the readings.
  - 33
  - 34

094549-08101  
FOIEBQ 2645466

1 In preferred embodiments of its third major indepen-  
2 dent facet or aspect, the invention is a method of provid-  
3 ing substantially absolute color standardization in sub-  
4 stantially all incremental printers of a product line.  
5 The method includes the step of, for at least one chroma-  
6 tic colorant, storing — for access by each printer — a  
7 numerical representation of an absolute perceptual parame-  
8 ter for at least one tone.

9 The method also includes the step of later retrieving  
10 and applying the stored representation to establish the  
11 printer dynamic range. The foregoing may represent a de-  
12 scription or definition of the third aspect or facet of  
13 the invention in its broadest or most general form.

14 Even as couched in these broad terms, however, it can  
15 be seen that this facet of the invention importantly ad-  
16 vances the art. In particular, while the above-discussed  
17 first two aspects focus piecemeal upon — respectively —  
18 establishment of a standard and its retrieval for use,  
19 this third facet contemplates the invention from a more-  
20 global perspective of the overall process.

21 This facet of the invention solves the problem of  
22 color uniformity by creating a process that directly grips  
23 and manipulates the entire printer dynamic range to a  
24 standard condition. This is based, however, simply and  
25 ingeniously on specification of at least one tone (one of  
26 which is preferably equal to a maximum tone, as will be  
27 seen) — not on a detailed calibration pervasive to the  
28 entire operating gamut.

29  
30 Although the third major aspect of the invention thus  
31 significantly advances the art, nevertheless to optimize  
32 enjoyment of its benefits preferably the invention is  
33 practiced in conjunction with certain additional features  
34 or characteristics. In particular, as noted above the at

1 least one tone preferably includes a tone that is equal to  
 2 a maximum tone. Also preferably the storing step includes  
 3 placing the numerical representation in each printer or  
 4 raster-image processor ("RIP") to be associated with each  
 5 printer; or in a software cache accessible to each printer  
 6 or raster-image processor.

7 In any of these cases it is further preferred that  
 8 the placing include memorizing the numerical representa-  
 9 tion in a read-only memory ("ROM") or an application-spe-  
 10 cific integrated circuit ("ASIC"). As is well known, ROM  
 11 types are available in a great variety — including pro-  
 12 grammable (PROM), erasable (EPROM), and electrically era-  
 13 sable (EEROM, EEPROM). Another, alternative, preference  
 14 is that the storing step include placing the numerical  
 15 representation in a printer driver used by each printer.

16 Yet another preference is that the applying step in-  
 17 clude closed-loop control based upon printing a test pat-  
 18 tern that nominally includes the maximum tone; and measur-  
 19 ing the test pattern with a calibrated sensor to derive a  
 20 comparable absolute perceptual parameter for the nominally  
 21 included maximum tone. In this case a subpreference is  
 22 that the closed-loop control include first comparing the  
 23 stored numerical representation of the perceptual parame-  
 24 ter with the comparable measured perceptual parameter; and  
 25 then, from differences found in the comparison, deriving a  
 26 correction function to be applied to image data in future  
 27 printing.

28 Another subsidiary preference is that the function  
 29 include a correction, based on the retrieved at least one  
 30 tone, that causes the printer perceptual output tones to  
 31 be a linear function of input data level. Yet another  
 32 preference is that the storing step include storing nu-  
 33 merical representations for plural tones; and the retriev-  
 34 ing step include retrieving the representations of the

plural tones; and the function include a correction, based on the representations of the plural tones, that causes the printer perceptual output tones to be a nonlinear function of input data level.

A further subsidiary preference is that the closed-loop control also include, in future printing, applying the correction function to image data.

Yet another, more basic preference is that the storing step include storing a numerical representation of a standard value of the absolute perceptual parameter; and also in this case that the method further include the steps of:

determining the absolute perceptual parameter for printers that represent worst-case performance within the product line, and

selecting the numerical representation and selecting printer operating conditions in view of the determined parameter for the worst-case performance, to ensure that in each printer of the product line the applying step will be able to force the dynamic range to encompass the standard value

All of the foregoing operational principles and advantages of the present invention will be more fully appreciated upon consideration of the following detailed description, with reference to the appended drawings, of which:

### BRIEF DESCRIPTION OF THE DRAWINGS

### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a diagram, highly schematic and not to scale, illustrating accuracy and repeatability concepts applicable to the invention — the ordinate representing magnitude of the various forms of possible error, and the abscissa representing time (and also, being at the zero-error point, representing a target color);

Fig. 2 is a color-error probability distribution representing color goals and performance in a printer product line;

Fig. 3 is a graph (not to scale) of luminosity vs. nominal inking density for uncorrected printer response and also for linearized response, after a conventional linearization procedure (i. e. without standardization of color, and accordingly showing uncertainty or error at the full-inking point) for two printing arrays that mark with different boldness: one inking nominally and the other inking overboldly;

Fig. 4 is a like graph of response following a conventional procedure, but for only a nominal-inking one of the two arrays assumed in Fig. 3 — and also incorporating expressly a superposed correction function that is only implicit in Fig. 3;

Fig. 5 is a like conventional graph for the other, overbold-inking one of the arrays assumed in Fig. 3;

Fig. 6 is a comparable set of graphs of only the two Fig. 4 and 5 correction functions — shown in both multiplicative and additive forms — but without the uncorrected response;

Fig. 7 is a flow chart, also highly conceptual and schematic, showing routine color correction with the invention in place — and also diversion of information flow for recalibration of the color-correction stage;



00045490 083101

1           Fig. 8 is a block diagram, also highly schematic,  
2           showing a test pattern — and also system modules that  
3           read and interpret the test pattern — to effectuate the  
4           Fig. 7 recalibration;

5           Fig. 9 is a graph like Fig. 3, but following a novel  
6           full-inking-point displacement, range rescaling and line-  
7           arization procedure according to the present invention,  
8           rather than conventional procedure (and accordingly show-  
9           ing standardization of color and near-absolute color  
10          correction);

11          Fig. 10 is a graph like Fig. 5, for the overbold-ink-  
12          inking array, but showing a superposed correction function  
13          according to the invention rather than a conventional  
14          function;

15          Fig. 11 is a graph like Fig. 9 but for an overligh-  
16          inking array rather than an overbold one;

17          Fig. 12 is a graph like Fig. 10 but for the over-  
18          light-inking array of Fig. 11;

19          Fig. 13 is a graph showing at a lower conceptual lev-  
20          el — namely, in machine-language or hardware-language  
21          terms — how the invention rescales received image data  
22          for printing by nominal-, overbold- and overligh-inking  
23          printing-element arrays respectively; and

24          Fig. 14 is a tabulation of all the perceptual parame-  
25          ters stored in a preferred embodiment of the invention.

26  
27  
28

09945492 08301  
T07E80" 26454660

1     DETAILED DESCRIPTION  
2     OF THE PREFERRED EMBODIMENTS

3  
4  
5     1.     BASIC AUTOMATIC LINEARIZATION IN THE FIELD

6  
7             Preferred embodiments of the present invention have  
8     some elements in common with earlier work. A general  
9     principle is the measuring of reflected energy from pri-  
10    mary color tiles or patches of graduated tonal density or  
11    darkness which are illuminated with a narrow-band light  
12    source (e. g. a light-emitting diode, LED).

13            Such operation is analogous to that of a classical  
14    densitometer. The reflected energy is received by a sen-  
15    sor, whose electrical output signal is correlated to meas-  
16    ured luminosity  $L^*$  and yellow-blue chrominance  $b^*$  via  
17    lookup tables.

18            In other words, reflectance-indicating signals are  
19    converted into  $L^*/b^*$  estimates using these tables. The  
20    estimated  $L^*$  and  $b^*$  values in turn are used to correct the  
21    printing system back to a known linear tonal response to  
22    input data.

23            (The invention is not limited to forcing a tonal re-  
24    sponse that is linear; another, different function can be  
25    adopted instead — and in this case it is likely to be  
26    preferable to select and store plural standard points  
27    along the tone gamut, rather than only a maximum tone. In  
28    addition, in purest principle the invention can be prac-  
29    ticed using a stored tone which is not at the extreme max-  
30    imum end of the tonal range, and this is within the scope  
31    of certain of the appended claims.)

32            The origin of the lookup tables is outside the lin-  
33    earization process itself. These tables are usually pre-  
34    pared in the factory for each printer with its line sensor



1           The refinement approach is better able to determine  
2 final small corrections very sensitively. This procedure  
3 is initiated either by a user or automatically by the host  
4 computer 41 (or even the printer 52).

5           Upon initiation of the relinearization, the original  
6 linearization functions 51 are channeled to the printer  
7 52, which invokes 53 a programmed series of steps 54 — to  
8 be discussed in detail below. The result is a new set of  
9 linearization functions 55, which then are substituted for  
10 the preexisting ones previously in the pipeline.

11          The basic color-linearization procedure, i. e. the  
12 series of steps 54 mentioned above, is as follows.

- 13
- 14       ▪ printing: A closed-loop color target 21 (Fig. 8),  
15       consisting of primary color ramps of different ink  
16       quantities, is halftoned and printed in the usual way  
17       — using all of the default (i. e. routine) settings  
18       and system configurations.
  - 19
  - 20       ▪ scanning: After allowing the ink to dry (preferably  
21       using a default drying-time algorithm), the system  
22       scans the target using the optical sensor 22 that is  
23       a standard part of the printer — and is commonly  
24       known as a "line sensor" or "color sensor". It has  
25       preferably three light-emitting diodes (LEDs) — am-  
26       ber, green and blue respectively — to provide illu-  
27       mination throughout the visible spectrum, for best  
28       sensitivity to the cyan, magenta, yellow and black  
29       colorants.

30          The sensor also has a single photodiode as de-  
31       tector. The LEDs are powered by a drive circuit 23  
32       synchronized with detection, for clear separation of  
33       color effects when desired.

1     ▪ signal preprocessing: Preliminary signal preparation  
2     26 provides digital form, independent gain adjustment  
3     for the respective color-signal channels, filtering  
4     and averaging. (At an even earlier, preliminary  
5     stage a black-point measurement is also used for set-  
6     ting of electronic gain and offset values; that rou-  
7     tine operation, sensing the darkness in a hole provi-  
8     ded in a printhead service-station region, is apart  
9     from the present invention.) Then the still-raw  
10    sensor readings 27 undergo color correction 31 (using  
11    the sensor precalibration mentioned above).

12           A first step here is conversion into perceptual  
13    parameters — luminosity or chrominance. More spe-  
14    cifically, readings for the yellow Y ramp are trans-  
15    lated into yellow-blue chrominance  $b^*$ ; and for all  
16    the other ramps, into luminosity  $L^*$ . These others  
17    include black K, cyan C, and magenta M; but also  
18    light cyan c and light magenta m if the printer has  
19    these supplemental colorants.

20           The special treatment for Y is adopted to over-  
21    come relatively low contrast in the luminosity scale  
22    for yellow. As is well known, such low contrast is  
23    essentially an intrinsic property of yellow; this ap-  
24    proach to measuring yellow is known in the art.

25           (The sensor as calibrated in its lookup tables  
26    yields perceptual values that still are good only for  
27    the purposes indicated, i. e. for measuring primaries  
28    within the small range of the primary color varia-  
29    tions — which is the operating range. Here the pre-  
30    cision and accuracy are adequate; but the sensor as  
31    thus calibrated should not be used for measuring any  
32    secondary or other constructed color.)  
33



1 can be traced directly to essentially three limitations in  
2 the related systems:

- 3
- 4     ▪ arguably inadequate sensor calibration;
- 5
- 6     ▪ no absolute full-saturation reference value; and
- 7
- 8     ▪ no objective to eliminate intraline inconsistency.
- 9

10 The first of these is significant because the color dif-  
11 ferences of interest here are relatively small in magni-  
12 tude. Therefore they could be swamped out — or in any  
13 event rendered badly imprecise — by relatively small cal-  
14 ibration variance such as may perhaps persist in some or  
15 all of the systems described in the earlier-mentioned Su-  
16 birada patent document.

17         The second is critical even if sensor calibration is  
18 adequate. In the absence of a nominal maximum-tone refer-  
19 ence for the product line, there is nothing with which to  
20 match each production printer in the line.

21         The third is essential because availability of infor-  
22 mation is not the same thing as its actual use. That is  
23 to say, actual intraline consistency requires an actual  
24 procedure that indeed makes use of both adequate sensor-  
25 calibration data and a maximum-tone reference value.

26

27         The present invention addresses all three of the lim-  
28 itations outlined above. Thus first, if desired, the in-  
29 vention can eliminate possible imprecision or inaccuracy  
30 of sensor-signal calibration into a perceptual color space  
31 (due for example to uncertain assumptions about media in-  
32 dependence of sensor calibration).

33         This step is a matter of calibrating the line sensor  
34 separately and specifically with each different printing

1 medium that is intended for use with the printer. Once  
2 given an absolute calibration to perceptual space, the  
3 sensor is ready to measure actual full-saturation tones in  
4 the printer — in a way that will later yield measurements  
5 directly comparable with lab measurements of nominal or  
6 standard full-saturation tones.

7  
8 Second, in preferred embodiments the invention de-  
9 fines and measures a nominal reference tone 62' (Fig. 9)  
10 for full saturation of each colorant that the printer  
11 product line uses. Thereby not only is the high-luminosi-  
12 ty end 69 (Figs. 3 through 5, and Figs. 9 and 10) of the  
13 dynamic range well defined — through printing and measur-  
14 ing on the bare printing medium — but the low-luminosity  
15 (or high-chrominance, for yellow) end 62' too is well de-  
16 fined.

17 That cutoff point is explicitly defined and measured  
18 as a standard for the product line. (For simplicity in  
19 the drawings, Figs. 9 through 12 illustrate essentially a  
20 first linearization, for each of the various cases, rather  
21 than the preferred relinearization 51-55 [Fig. 7] dis-  
22 cussed earlier; illustration of the fine corrections in  
23 such a relinearization would be difficult to show and see,  
24 for the very reason of their being very small refinements  
25 of the previous correction values.)

26 Comparing the nominal tone 62' (Fig. 9) with Fig. 3,  
27 in which the upper curve 16 represents the natural system  
28 response in a printer that has a nominal-dropweight print-  
29 head, it can be seen that this second provision of the  
30 invention simply establishes the nominal maximum tone or  
31 cutoff for a nominal printhead. This step cannot be  
32 performed in the field (i. e. in an end-user's facility)  
33 — or even at the factory, in the sense of being any part  
34 of the production-line procedures — because this is a



09945492-033101  
T07E80" 26454660

1 step which must be performed on behalf of the entire prod-  
2 uct line.

3 Accordingly the definition and measurement parts of  
4 the preferred embodiments are performed at a product-de-  
5 sign or -redesign stage. In usual idiom such measurements  
6 are performed in the "laboratory" rather than the factory.

7 The definition step preferably includes printing test  
8 patterns with a representative sampling of production pro-  
9 totype printers, and the readings compared and combined to  
10 obtain a composite that can then be treated as nominal and  
11 standard for the product line. This printing is done not  
12 only with actual printers representing the product line  
13 but also with the ink-and-printing-medium sets that will  
14 actually be used, to optimize the readings specifically  
15 for those ink-medium sets.

16 Most highly preferred practice of the present inven-  
17 tion includes measuring the standard cutoff tones 62' us-  
18 ing a high-quality photometer, for instance an automatic  
19 recording double-beam spectrophotometer with a reflectance  
20 attachment. Within the scope of certain of the appended  
21 claims, however, are many less-stringent approaches.

22 These include using a handheld colorimeter of the  
23 kind described in the coowned U. S. patent 5,272,518 of  
24 Vincent, or using a printer-mounted one such as taught in  
25 another coowned patent of Vincent, U. S. 5,671,059 and in  
26 the above-mentioned patent document of Thomas Baker, or  
27 even using the calibrated onboard line sensors in the  
28 printers themselves — e. g. even those printers used to  
29 produce the standard tone printouts. What is key is to  
30 obtain a tone reading that is susceptible to direct and  
31 reasonably reliable comparison with sensor readings that  
32 will later be made automatically in the field by printers  
33 in the product line.

1. In purest theory even an arbitrary tone reading could  
2 be used as a standard. Such a choice, however, in general  
3 would fail to make best use of the dynamic range — and  
4 thus the intrinsic color gamut — of the printer.

5 It is important that the measurements include check-  
6 ing the product line and its design to determine worst-  
7 case values for dropweight and other parameters that  
8 closely affect inking density, particularly at the maxi-  
9 mum-tone end of the dynamic range. The standard value to  
10 be stored — and also all the other operating conditions  
11 of the printer — should be chosen so that every printer  
12 in the product line, even if it is operating at an extreme  
13 of operating performance, be able to reach the standard  
14 values established and stored.

15  
16 While definition and measurement are clearly labora-  
17 tory rather than factory operations, the next step — sto-  
18 rage of the resulting reference data — may be regarded as  
19 a closer case, since these data are in fact stored in each  
20 printer on the production line. The manner in which the  
21 data are primally stored, however, usually involves em-  
22 bedding the information in design data for an ASIC or some  
23 type of ROM.

24 Development of such design data is commonly seen as a  
25 laboratory (not factory) function. Engineers prepare not  
26 only abstract numerical descriptions of the data but also  
27 lithographic or like masters to be later used directly in  
28 fabrication of the multiple layers of integrated circuits  
29 — or, in some cases, prepare master data blocks for load-  
30 ing into firmware memories. The engineering tasks are  
31 performed in the lab.

32 The ASIC or ROM, however, is then manufactured in  
33 large quantities, automatically following the laboratory-  
34 developed specifications. This manufacturing step, re-

1     gardless of whose facility performs it, is essentially a  
2     factory operation.

3             At the factory, each ASIC or ROM is then installed  
4     into a respective one of the printers in the production  
5     line. It is unclear whether the "data storage" occurs at  
6     the early instant of lab embedment of the information in  
7     fabrication masters, or at the later instant of automated  
8     realization of the embedded information into production  
9     components.

10            As can be seen, it is basically a semantic question  
11     whether the storage step is a laboratory or factory func-  
12     tion. In any event the definition, measuring and storage  
13     are all parts of an overall procedure for practicing pre-  
14     ferred embodiments of the invention; and these parts are  
15     all performed either for or on behalf of the printer manu-  
16     facturing company.

17  
18            Third, the invention calls for use of the stored  
19     full-saturation reference tone in an automatic field pro-  
20     cedure that actually forces 115 (Fig. 9) the low-luminosi-  
21     ty point 64 for a nonnominal-dropweight printhead to match  
22     the adopted standard 62' for all units in the product  
23     line. With that point under control, near-absolute cali-  
24     bration can then be completed by an essentially common  
25     linearization in which the entire natural response curve  
26     117 for a nonnominal head is replaced by a substantially  
27     linear response 119 that drives to the standard low-lumi-  
28     nosity level 62'.

29            Furthermore that entire linear response 119 of the  
30     thus-corrected nonnominal head is very nearly congruent  
31     with the entire linear response 118 of a nominal head.  
32     The invention thus comes very close to erasing visible  
33     traces of the distinction between nominal and nonnominal

1 printheads: not only intramachine linearity but also in-  
2 traproduct-line near-absolute consistency is the result.

3 It is in this part of the procedure that the defined,  
4 measured and stored tone actually comes into physical be-  
5 ing — in the sense of its being physically, colorimetri-  
6 cally replicated as:

- 7
- 8     ▪ a tonal value which the printer will actually print
- 9         whenever the low-luminosity tone is specifically in-
- 10        voked by input image data; and also
- 11
- 12     ▪ a tonal value to which the printer linearizes nearly
- 13         all other tones within its dynamic range.
- 14

15 (The word "nearly" is included here because the stored  
16 low-luminosity tonal value in principle has no effect at  
17 all on the single tone at the extreme high-luminosity end  
18 of the range. In addition, in some cases it is possible  
19 that some tones immediately adjacent to that one may not  
20 be affected by the standard low-luminosity value.)

21 The physical forcing of the low-luminosity endpoint  
22 64 to the stored value 62' is accomplished by an entirely  
23 new set of conversion terms or factors 65 (Fig. 10). By  
24 comparison with the previously discussed conceptual show-  
25 ings in Figs. 4 and 5, it can now be seen that — unlike  
26 the previously stated absence of causal connection between  
27 the nominal and nonnominal cases — there is now a cross-  
28 talk or causal relation between the two cases.

29 More specifically, here the conversion function 65  
30 links the two cases by making the nonnominal machine act  
31 just as the nominal machine acts. The right end of the  
32 conversion function 65 (and linearized response 119) no  
33 longer converges to the right end of the natural nonnomi-  
34 nal response curve 117 as was the case in the related art.

1           This conversion function incorporates within it the  
2 necessary step 115 (upward for a high-dropweight head).  
3 Therefore the new function 65 is not merely a conceptual-  
4 mirror-image complement of the natural response 117 — as  
5 were the functions 61, 63 (Figs. 4 and 5).

6           Another comparison of the correction function 65 with  
7 the earlier forms appears in the earlier-discussed graph  
8 of the function as a multiplier M, 65 (Fig. 6). This view  
9 offers another kind of direct graphical comparison with  
10 the functions 61, 63 used heretofore.

11           Here the new multiplier 65 is seen to depart from the  
12 earlier ones in that the right end of the graph does not  
13 return to the base level 1.0 but rather ends at an eleva-  
14 ted position. When this multiplicative correction func-  
15 tion 65 is applied to the original nonnominal response  
16 function 117, the curvilinear components of the two func-  
17 tions 65, 117 neutralize one another — yielding a recti-  
18 linear overall response, which may be seen as an inclined  
19 straight line 67.

20           The fact that this line 67 is angled toward the ele-  
21 vated position reveals that one component (the vertical  
22 step) of the overall correction is not merely neutralizing  
23 nonlinearities. Rather it is directly forcing the low-lu-  
24 minosity cutoff of the dynamic range in hardcopy printouts  
25 to match the same standard low-luminosity cutoff figure  
26 stored in the laboratory.

27           At intermediate points between the right-hand and  
28 left-hand ends of the correction function 65, the angled  
29 line 67 indicates how this matching portion of the adjust-  
30 ment is distributed over the dynamic range — maintaining  
31 linearity while accommodating the desired luminosity step  
32 115 (Fig. 9). The same distribution of the correction  
33 throughout the range appears in the additive version 65'  
34 (Fig. 6) of the correction, with its corresponding in-

1 clined straight line 67' departing from the horizontal  
 2 zero value implied for earlier procedures.

3  
 4 Measurements of residual color error, particularly at  
 5 the low-luminosity end of the dynamic range for the pri-  
 6 mary colorants, indicate that the absolute accuracy is im-  
 7 proved from the previously mentioned 5 dL\* to better than  
 8 1.5 dL\*. It is believed that as a result an even more  
 9 significant improvement is obtained in color consistency  
 10 for colors produced by combining the primaries.

11 The low-luminosity  $L^*_{MIN}$  points 62, 64 and 62' (Figs.  
 12 3 through 6, and Figs. 9 and 10), are in effect anchor  
 13 values that participate in controlling the slope of the  
 14 linearized response in each printer. The invention stan-  
 15 dardizes this  $L^*_{MIN}$  point in all the machines throughout a  
 16 product line.

17 At the other end of the dynamic range, the high-lu-  
 18 minosity  $L^*_{MAX}$  points 69 are relatively very well defined.  
 19 Since the two endpoints of the range are now much more  
 20 uniform, all other printed densities too, in these ma-  
 21 chines, tend to match those in the standard response.

22  
 23 If field measurements for a particular colorant in a  
 24 particular printer yield a low-luminosity point 64 that is  
 25 in fact lower than the nominal, this must mean that the  
 26 printer is applying excessive amounts of that colorant, at  
 27 least in that low-luminosity part of its operating range  
 28 (i. e. maximum colorant saturation). What is necessary  
 29 then is to decrease the amount of ink of that color, in  
 30 just the right proportion to inhibit the actual tone den-  
 31 sity (amplify the actual luminosity) to the nominal value  
 32 — and this is exactly what the printer automatically does  
 33 in the field.

1           If instead field measurements yield a low-luminosity  
2 point 64' (Fig. 11) that is higher than the nominal, this  
3 must mean that the printer is applying inadequate amounts  
4 of that colorant, at least in that low-luminosity part of  
5 its operating range (i. e. maximum colorant saturation).  
6 What is necessary then is to increase the amount of ink of  
7 that color, in just the right proportion to augment the  
8 actual tone density (suppress the actual luminosity) to  
9 the nominal value — and the printer does this too, all  
10 automatically, in the field.

11           It has not yet been shown exactly how this inhibition  
12 or augmentation of tone density (or the corresponding am-  
13 plification or suppression of luminosity) is accomplished.  
14 In all of the graphs discussed above, the abscissae repre-  
15 sent exclusively the nominal ink density — that is to  
16 say, the density as expressed at a relatively high concep-  
17 tual level, namely tonal values in an image-data file 43  
18 (Fig. 7).

19           Considered instead at a lower level conceptually, in  
20 actual machine-language terms, conversion for a nominal-  
21 dropweight printhead is a remapping 71 (Fig. 13) of all  
22 the image data from nominal tones, again on the abscissa  
23 70, to hardware tones now plotted along the ordinate 79.  
24 This remapping 71 appears as upward-convex due to the lin-  
25 earization requirement as before.

26           More significantly to the present explanation, the  
27 remapping also downsamples (i. e. interpolates) nearly all  
28 the tone or density numbers 0-255 to a shorter overall  
29 scale 0-230. That is, if the maximum density 75 handled  
30 in the system is hexadecimal 255, this maximum tone number  
31 is remapped 71 to a new density number 76, namely hexadec-  
32 imal 230 as shown.

33           The scale and thereby the overall dynamic range, for  
34 a nominal head, is foreshortened by roughly ten percent.

1 For a high-dropweight head, however, the conversion 65  
2 (Fig. 10) is a more-stringent remapping 72 (Fig. 13) —  
3 with an overall reduction of density numbers from hexadec-  
4 imal 255 to a lower new density number 77, namely e. g.  
5 hexadecimal 205 as shown (or e. g. 200). That is, for  
6 such a high-weight head the overall scale 0-255 shrinks to  
7 0-205.

8 The purpose of this across-the-board downscaling is  
9 to accommodate a low-dropweight head, which as above-men-  
10 tioned requires augmented density, also recognized as sup-  
11 pressed luminosity. For the weakest permissible printhead  
12 the mapping 73 from nominal density (again, image-data  
13 numbers) 70 to hardware-language density 79 is one-to-one  
14 at the maximum-density point 78: an input 75 of hexadeci-  
15 mal 255 maps to an output 78 that is unchanged — still  
16 hexadecimal 255 — and only the intermediate values are  
17 shifted, as the upward-convex curve 73 shows, to accom-  
18 plish linearization.

19 Relative to the nominal and high-dropweight heads,  
20 however, this unchanged or one-to-one maximum-density re-  
21 mapping 73 represents a scale expansion. Hence at the ma-  
22 chine level, considered relative to the dynamic range of a  
23 nominal head, that of a weak head is expanded while that  
24 of an overstrong head is contracted.

25  
26 The invention thus discards dynamic range for not  
27 only overweight inkdrops but also nominal-weight inkdrops.  
28 In rare cases some desired colors may fall out of gamut as  
29 a result.

30 Successful practice of the invention therefore calls  
31 for careful machine and printhead design to ensure that  
32 the gamut is wide enough for the intended market. This  
33 can be accomplished by careful engineering adjustments of  
34 ink chemistry, print media, dropweight ranges and all the



1 other factors common in inkjet printing — and the corre-  
2 sponding parameters in the several other forms of incre-  
3 mental printing.

4  
5 All such remapping is performed in the same stroke  
6 with the linearization 44 (Fig. 7). Hence the full power  
7 of the halftoning stage 46 is advantageously applied to  
8 spread out the impact all of the tonal adjustments alike.

9 By the same philosophy of the invention, preferred  
10 embodiments include neither conventional depletion nor the  
11 propletion principle of the Borrell document. Algorithms  
12 for both can be used in conjunction with the present in-  
13 vention; however, depletion removes posthalftoned dots on  
14 media based on criteria that encompass only gross inking-  
15 volume concerns and thus fail to take into account finer  
16 image-quality effects.

17 Depletion in fact commonly introduces artifacts such  
18 as graininess. Prehalftoning corrections according to the  
19 preferred embodiments of this invention are not only more  
20 elegant but also, again, invoke the mechanisms of the  
21 halftoning stage 46 to integrate all the image features  
22 into a properly textured whole.

23 Once beyond the laboratory printing-and-measurement  
24 stages, these remarkable accomplishments are achieved with  
25 a substantially unmodified six-dollar line sensor — not a  
26 spectrophotometer, not even a fifty-dollar colorimeter.  
27 With the same direct material cost as competing products  
28 of the same manufacturer, this invention provides color-  
29 correction precision that is twice as fine, and accuracy  
30 that is more than three times finer.

31  
32

1 3. HARDWARE, PROGRAM AND STORAGE IMPLEMENTATION

2

3 As the invention is amenable to implementation in, or  
 4 as, any one of a very great number of different printer  
 5 models of many different manufacturers, little purpose  
 6 would be served by illustrating a representative such  
 7 printer. If of interest, however, such a printer and some  
 8 of its prominent operating subsystems can be seen illus-  
 9 trated and discussed in several other patent documents of  
 10 the assignee, Hewlett Packard — such as for example the  
 11 previously mentioned document of Thomas Baker, which par-  
 12 ticularly illustrates a large-format printer-plotter model  
 13 suited for use as a multitask machine.

14

15 The most highly preferred embodiment of the invention  
 16 operates in a printer that has three different printmode  
 17 quality levels, respectively designated "normal", "best"  
 18 and "superbest". For nearly all printing media of inter-  
 19 est, the printmodes were developed carefully keeping in  
 20 mind the maximum uniformity possible — in terms of all  
 21 the elements that come into play in color correction — in  
 22 such a way that a calibration performed for the best mode  
 23 can be translated into normal and superbest without stor-  
 24 age of different minimum  $L^*$  or maximum  $b^*$  values.

25 Engineering of printmodes, balancing the speed and  
 26 number of passes to obtain a selected level of quality, is  
 27 known in the art. If preferred, however, the modes can be  
 28 designed much more routinely at the cost of merely storing  
 29 a few more  $L^*$  and  $b^*$  numbers.

30 The number of media designed for use with the most  
 31 highly preferred embodiment is six. For one of these me-  
 32 dia and one of the three printmodes (superbest), however,  
 33 it was found preferable to use a different perceptual-pa-  
 34 rameter set than for that medium with the other two modes.

1           Based on this preference and otherwise using the max-  
2   imum-uniformity approach noted above, the number of dif-  
3   ferent mode-media combinations needing separate maximum-  
4   nominal tone storage is seven. For each of these seven  
5   combinations, six values are stored — for a total of for-  
6   ty-two values (Fig. 14).

7  
8  
9  
10           The above disclosure is intended as merely exemplary,  
11   and not to limit the scope of the invention — which is to  
12   be determined by reference to the appended claims.

09945492-083101  
TOP SECRET